Final Report

Observations of Ice Motion in the Marginal Siberian Seas

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I. Narrative Documentation

A. Long-term goals

Our goal is to determine the status and fate of radionuclides in the Arctic and North Atlantic. In Particular, we are responding to the concerns about concentrations, transport pathways, and fate of radionuclides in the Arctic ecosystem.

B. Objectives of this effort

The Ob and Yenisey Rivers, which flow into the Kara Sea, have been identified as potential sources of radionuclides. After the contaminants are discharged into the sea, ice motion and surface ocean currents are the principal agents of redistribution and possible long-range transport. Our objective is to understand the role of sea ice in transporting riverine contaminants from the river outflow regions, through the Kara Sea, and into the adjacent Barents Sea and Arctic Basin.

C. Approach

Our approach is to regard sediment as a surrogate for pollutants. Although some sediment found in sea ice may be relatively free of radionuclides, we do not expect to find radionuclides in sediment free ice. Sediment is a precondition for

the presence of radionuclides. One advantage of linking the pollutants to sediment is that we can take advantage of existing work by arctic geological oceanographers, e.g., on uptake and transport processes.

Sediment is incorporated into the newly forming ice cover by a process called suspension freezing. Individual ice crystals may first nucleate to the very fine grained sediment in the water column. Once formed, the ice crystals aggregate and effectively filter sediment as the flocked frazil ice moves through the water column. Further filtration is accomplished as turbid water percolates through the floating frazil ice cover. The observational evidence shows that almost all of the sediment found in first year ice is contained in the frazil layers. The uptake of pollutants into the ice depends on the presence of suspended particulate matter (SPM) in the water column.

We are presently researching Kara Sea ice processes to identify the source regions of sediment-laden ice, quantify the areal production of possibly polluted ice, determine the pathways of ice transport, and estimate survivorship of ice during the summer melt.

We assume: (1) that during the October freeze-up, polluted drift ice is primarily formed between the 20-m and the 50-m isobaths, and (2) that drift ice formed in the flaw lead after January tends not to survive the summer melt. Our preliminary findings indicate the results will be sensitive to these two assumptions. If turbid waters are limited to regions much shallower than 50-m and if melting processes are more intense, then sea ice will merely redistribute pollutants from the shallow to the deeper portions of the Kara Sea. In this case, the Kara Sea would be a sediment trap and most pollutants would be consigned to the depths. Conversely, if turbid waters occur well beyond the 50-m isobath during the October freeze-up, and if the summer melt is largely limited to the western regions, then the Kara Sea would be a major exporter of polluted ice to the Arctic Basin and Eastern Barents Sea.

We participated in the Russian/Norwegian 1995 Expedition to the Kara Sea. Our goal was to survey the horizontal and vertical extent of sediment suspended in the water column. It is this sediment which can be taken up by the formation of October drift ice. Our expectation is that the large scale distribution of suspended matter in the Kara Sea will be easily identified with some combination of geophysical parameters, e.g. depth, water mass characteristics, or recent local turbulent mixing.

During the 1995 Russian/Norwegian expedition to the Kara Sea we surveyed the spatial structure of SPM. We equipped a Sea-Bird CTD with an off-the-shelf backscatter nephelometer and measured the suspended solid concentration at ocean stations throughout the Kara Sea.

D. Accomplishments

The following tasks have been completed:

1. Monthly mean fields of ice motion have been analyzed for the Arctic Basin, the Kara and Laptev seas using DARMS and Argos buoy observations supplemented by winds. Figure 1 shows the overall mean field of ice motion.

2. The Arctic and Antarctic Research Institute, St. Petersburg (AARI) meteorology, riverine flow, water masses and thermohaline structure, hydrochemical regime, wind-induced wave characteristics, water exchange and circulation, tides, level and ice regimes of the Kara, Laptev and East-Siberian Seas.
3. Probabilities of whether sea ice produced in the Kara Sea advects into the Arctic Basin, Barents Sea or stays in the Kara Sea have been analyzed using the climatological mean field of ice motion. (Figure 2-4)
4. Areal production rates for winter ice produced in the flaw leads of the Kara Sea have been estimated for 1979 through 1993 using ice charts and fields of ice motion. (Figure 5)
5. Backwards trajectory analysis has been applied to ice cores taken during the 1994 US/Canada Arctic Ocean Section.
6. Estimates of drift speeds of sea ice from the Laptev and Kara Sea have been made. (Figure 1)
7. Possible areas of contamination by sea ice from the East Siberian, Laptev and Kara Seas have been identified. (Figure 6)

E. Results

Our primary results are an analysis of the ultimate fate of sea ice produced in the Kara Sea during a typical winter. Using the mean field of ice motion (e.g. Figure 1), we have estimated the probabilities of whether a piece of ice that forms in the Kara Sea will travel far enough during the winter to be exported from the Kara Sea to either the Barents Sea, or into the Arctic Basin. Figures 2 - 4 show the probabilities of these different fates.

As in our study of the Laptev Sea, areal production of sea ice in the shallow waters of the winter flaw leads of the Kara Sea has been estimated for the winters of 1979 to 1992. The interannual variability of these areas is shown in Figure 5. The mean annual shallow water production rates are 72,000 km^2 for October ice, and during the ensuing winters, a mean flaw lead production of 132,000 km2 has been found for a mean annual ice production of 204,000 km2. Unlike the Laptev Sea, however, care should be taken in interpreting these results since our analysis of the ultimate fate of sea ice formed in the Kara Sea imply that very little ice produced in the area of the flaw leads where radionuclides can be entrained is exported from the Kara Sea. The mean area of October and flaw lead ice exiting into the Barents Sea and Arctic Basin can then be calculated by integrating the product of area and probability. We estimate that in the mean, only 20,000 km2 of this sea ice is produced in its shallow waters.

Although our estimates of export of shallow water ice from the Kara Sea are low compared to the Laptev Sea (20,000km2 vs. 256,000km2), sea ice produced over the deeper waters of the Kara Sea can potentially carry contaminants deposited onto the sea ice aerially. From its northern regions, the Kara Sea exports 95,000 to 185, 000 km2 of sea ice into the Arctic Basin, and 110,000 to 278,500 km2, into the Barents Sea. On average a piece of ice exported from the Kara Sea would take 2-3 years to advect through Fram Strait and into the biologically rich waters of the Greenland Sea, but simulations of lagrangian drifters using the monthly

fields of ice motion from 1979-1994 show that this transit time can be as short as 9 months.

Lagrangian drifter simulations ("forward trajectory simulations"), from the Laptev and East Siberian Seas have also been run to quantify the possible areas of contamination. Sea ice from the Kara was found to be exported primarily into the Arctic Basin and the Barents Sea. Of the ice that was exported into the Arctic Basin from the Kara Sea, all trajectories were found to advect towards Fram Strait and to a smaller extent into the Barents Sea. Simulations from the Laptev were found to mostly advect towards Fram Strait and some into the Barents Sea. Simulations from the East Siberian Sea were also found to merge with the Transpolar Drift Stream and advect towards Fram Strait, however, some simulations were also found to advect into the Beaufort Gyre where the ice could potentially carry pollutants to Alaska. No simulations from the Kara or Laptev Sea were found to enter the Beaufort Gyre. (Figure 6)

F. Impact for science or systems applications

Ice and water mass exchange between the Siberian shelves and the Polar Basin is identified as a key issue of the ACSYS program of the World Climate Research Program and in the new European initiative for the study of arctic processes. An understanding of ice motion is central to arctic shelf exchange processes. Our study of areal ice production can easily be modified to estimate ice volume production and hence salt production required for an understanding of arctic intermediate water mass formation. Forward and back trajectory analysis can be applied to any type of sample taken from the Arctic Basin.

Many other pollutants, e.g. agricultural pesticides and industrial by products, may also be incorporated into sea ice by suspension freezing. As our study uses sediment as a surrogate for radioactive pollution, it is equally applicable to the long-range transport of other forms of pollution.

G. Transitions Expected

Our methods should be applied to a more in-depth study of the sea ice processes of the East Siberian Sea.

H. Relationship to other projects

Our research is an essential component in understanding the role of sea ice in the global consequences of nuclear waste management.

We have been collaborating with other ANWAP researchers on their projects, most notably: Stephanie Pfirman, "Potential contribution of radionuclides from drifting, river-influenced Arctic sea ice;" Debra Meese and Terry Tucker, "Radionuclide contaminants in central Arctic sea ice;" and Ed Landa, "Mobilization and Transport of Radionuclides to the Kara Sea by the Ob and Yenisey River."

II. Statistical Information

A. List of Publications

1. Rigor, I. and R. Colony, in press: Sea Ice Production in the Laptev Sea, *Science of the Total Environment.*
2. *Pfirman, S.L, J.W. Kögeler, I. Rigor, in press: Potential Shortcuts for Transport of Contaminants from the Kara Sea, Science of the Total Environment.*
3. *Pfirman, S.L., R. Colony, D. Nürnberg, H. Eicken, I. Rigor, accepted: Reconstructing the Origin and Trajectory of Drifting Arctic Sea Ice, Journal of Geophysical Research.*
4. Rigor, I. and R. Colony, in preparation: Sea Ice Production in the Kara Sea.
5. Rigor, I. and R. Colony, in preparation: Sea Ice Motion in the Marginal Seas.
6. Landa, E., E. Reimnitz, D. Beals, J. Pochkowski, and I. Rigor, in preparation: Transport of 137 Cs and 239,240 Pu by Ice Rafted Debris in the Arctic Ocean.

B. Number of Graduate Students

None

C. Patents

None

D. Presentations

1. Sea Ice Motion in the Marginal Siberian Seas, *Arctic Nuclear Waste Assessment Workshop, Snowbird, Utah, May 1996.*

E. Committee Service

None

F. Awards

None

G. Russian Participation

Under ANWAP funding, the University of Washington had a $62,000 subcontract with the AARI.